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FAULT-TREE ANALYSIS OF CASCADED H-BRIDGE INVERTER ACCORDING TO VARIOUS SWITCHING SCHEMES

FEEL-SOON KANG

Department of Electronics and Control Engineering, Hanbat National University, Korea

ABSTRACT

Cascaded H-bridge multilevel inverter increases the number of output voltage levels by connecting H-bridge cells in series. More H-bridge cells ensure high qualified output voltage waves similar to sinusoidal wave and increase redundancy in the viewpoint of safety. However, the increase of the number of H-bridge cells grows up the possibility of failure of the system due to the increased circuit components and complex control signals.

Cascaded H-bridge multilevel inverter can apply various pulse width modulated switching scheme to obtain a sinusoidal output voltage wave and to compensate the lack of H-bridge cells. For various PWM switching methods suitable to cascaded H-bridge multilevel inverter, each Fault-tree is given to analyze the reliability and failure rate. After FTA, the switching scheme is verified by simulation and experiments.

KEYWORDS: Fault-Tree Analysis (FTA), Multilevel Inverters, Pulse Width Modulation (PWM) & Total Harmonic Distortion (THD)

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Original Article

INTRODUCTION

Cascaded H-bridge multilevel inverter has several advantages in practical applications such as reliability, redundancy, and modularity [MALINOWSKI et al, 2010, ABU-RUB et al, 2010]. The objective of multilevel inverter is to generate high voltage by using lower voltage rating devices connected in series. It has a possibility to obtain high quality output voltage by synthesizing multi levels in output voltage. However, it increases the number of switching devices and other components resulted in the increase of complexity problem and system cost [RODRIGUEZ et al, 2002, FRANQUELO et al, 2008, LAI et al, 1996, TOLBERT et al, 1999]. At the same time, the complexity in control and circuit structure degrades the reliability and increases the failure rate. Therefore, we need to estimate the failure rate and evaluate the reliability before designing new circuit topologies and applying modified switching methods.

PWM switching technique is generally used to improve the total harmonic distortion of the output voltage. In this case, switches are operated in high switching frequency resulted in high switching losses. To alleviate this problem, a modified switching method for the cascaded H-bridge multilevel inverter has been introduced in [B. C. JEONG, et al, 2013]. In this reference, the lower H-bridge cell generates a fundamental voltage level, and the upper H-bridge cell produces a pulse width modulated wave. Since the output terminals of both H-bride cells are connected in series, the inverter obtains pulse with modulated five levels in the output

voltage. This cascaded circuit structure guarantees high qualified output voltage waves similar to sinusoidal wave and increase redundancy in the viewpoint of safety. However, the increase of the number of H-bridge cells grows up the possibility of failure of the system due to the increased circuit components and complex control signals.

In this paper, we analyze various PWM switching methods by using Fault-tree and then each switching scheme is applied to the cascaded H-bridge multilevel inverter to evaluate the reliability and the possibility of failure rate. After FTA, each switching method is verified by simulations and experiments

CASCADED H-BRIDGE MULTILEVEL INVERTER

Cascaded H-bridge multilevel inverter consists of an array of switching devices (H-bridge cell) and independent dc voltage sources. Figure 1 shows a circuit con Figure ration of a cascaded H-bridge multilevel inverter employing two independent input dc voltage sources. It can add more H-bridge cells in series to increase the number of output voltage levels. In this paper, FTA only is considered on 5-level output voltages for the convenience.

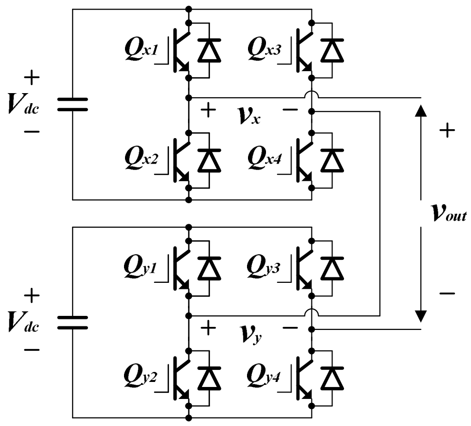

Figure 1: Cascaded H-Bridge Multilevel Inverter Employing Two H-Bridge Cells

General PD (Phase Disposition) Switching Method

Figure 2(a) shows a general switching pattern based on phase disposition (PD) method. It needs one reference voltage (v_{ref}) and four carrier waves (v_{c1}, v_{c2}, v_{c1-}, v_{c2-}). By comparison of the reference voltage and carrier waves, control signals for switches are obtained. Four switches are used to generate pulse width modulated waves with high switching frequency. Other switches are working for generating zero-level or fundamental V_{dc} voltage level.

Figure 2(b) shows a Fault-tree when PD switching is applied to cascaded H-bridge multilevel inverter. The failure of the inverter is divided into two groups; upper H-bridge failure and lower H-bridge failure. The control signal failure depends on reference signal and four carrier signals.

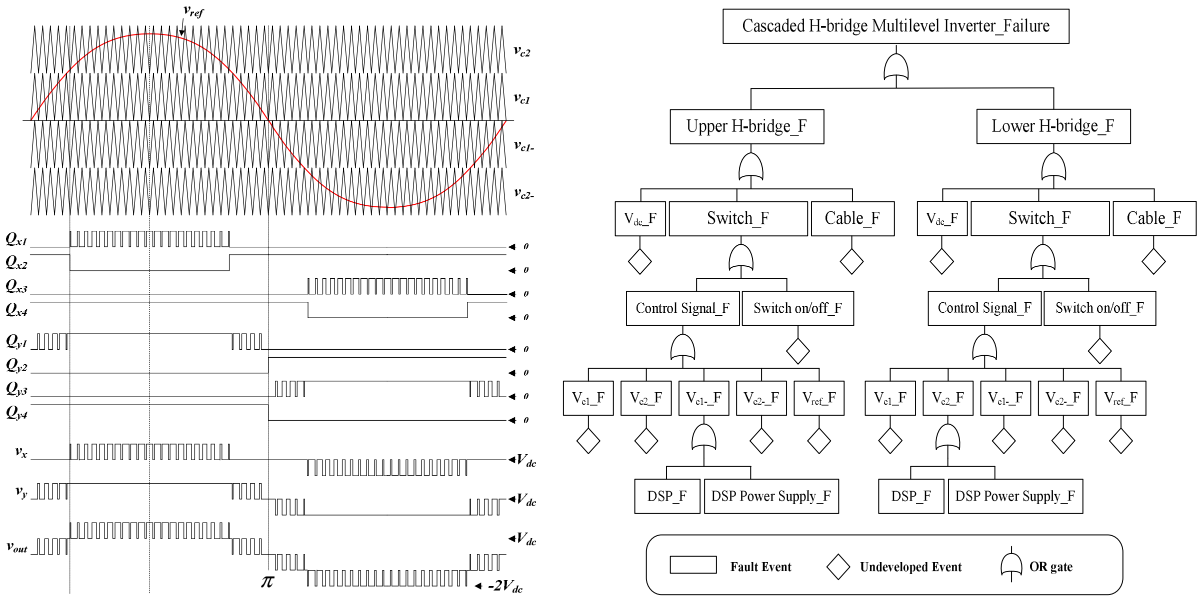

Figure 2: Phase Disposition, (A) Switching Pattern, (B) Fault-Tree of PD Method

Modified PD Switching Pattern

Figure 3 shows a modified switching pattern based on phase disposition (PD) method [B. C. JEONG, et al, 2013]. It also needs one reference voltage (v_{ref}) and four carrier waves (v_{c1}, v_{c2}, v_{c1-}, v_{c2-}). By comparison of the reference voltage and carrier waves, control signals for switches are generated. By the operation of two switches in the upper H-bridge cell, it can generate pulse width modulated waves in the output voltage. When the reference voltage is lower than the carrier waves (v_{c1} and v_{c1-}) or (v_{c2} and v_{c2-}), Q_{x3} . repeats on and off to generate chopped waves. By summing this chopped wave to the fundamental voltage level, the output voltage has linearly increased pulse waves. Two switches in the upper H-bridge cell are working for the generation of PWM waves with high switching frequency. Other switches in the lower H-bridge cell are operated in a fundamental frequency. The energy transferred loads from input sources are proportional to the area of voltage waves. It means most energy is delivered to the load from the voltage source in the lower H-bridge cell. In the modified switching method, all switches in the lower H-bridge cell are operated in a fundamental frequency. From this reason, the modified switching scheme has a merit for reducing switching losses compared with the prior switching method given in Figure 2(a).

Figure 3(b) shows a Fault-tree when modified PD switching is applied to cascaded H-bridge multilevel inverter. The failure of the inverter is divided into two groups; upper H-bridge failure and lower H-bridge failure. The control signal failure depends on reference signal and four carrier signals. As shown in both Fault-trees, there are no differences in hierarchy because they have the same carrier and reference wave. It means that the modified PD switching can reduce the switching losses compared to the general PD method, but in the viewpoint of reliability, the modified PD switching method is equal to that of the general PD switching method.

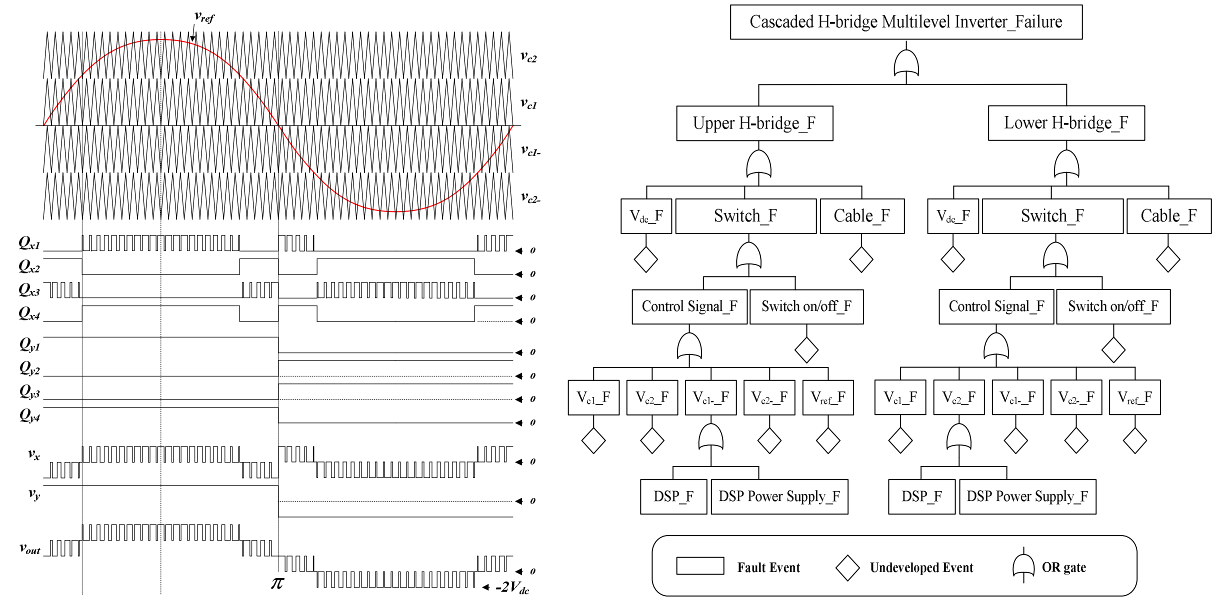

Figure 3: Modified Phase Disposition, (A) Switching Pattern, (B) Fault-Tree of Modified PD Method

Bipolar Switching Pattern

As shown in Figure 2(a) and Figure 3(a), they need a single reference voltage and four carrier waves to generate five levels in the output voltage. But in bipolar switching method as given in Figure 4(a), it can be realized by a single reference voltage and one carrier wave.

As shown in Figure 4(b), Fault-tree is simplified at the hierarchy of carrier waves. It means that bipolar switching can reduce the risk of control signal failure compared to PD switching methods. However, this method has a problem of PWM generation. Because the chopped waves increases or decreases their pulse width with a continuous rate, the output voltage has a larger voltage at the variation point of voltage level. It will increase THD of the output voltage. Unipolar switching method also shows similar results to bipolar switching method.

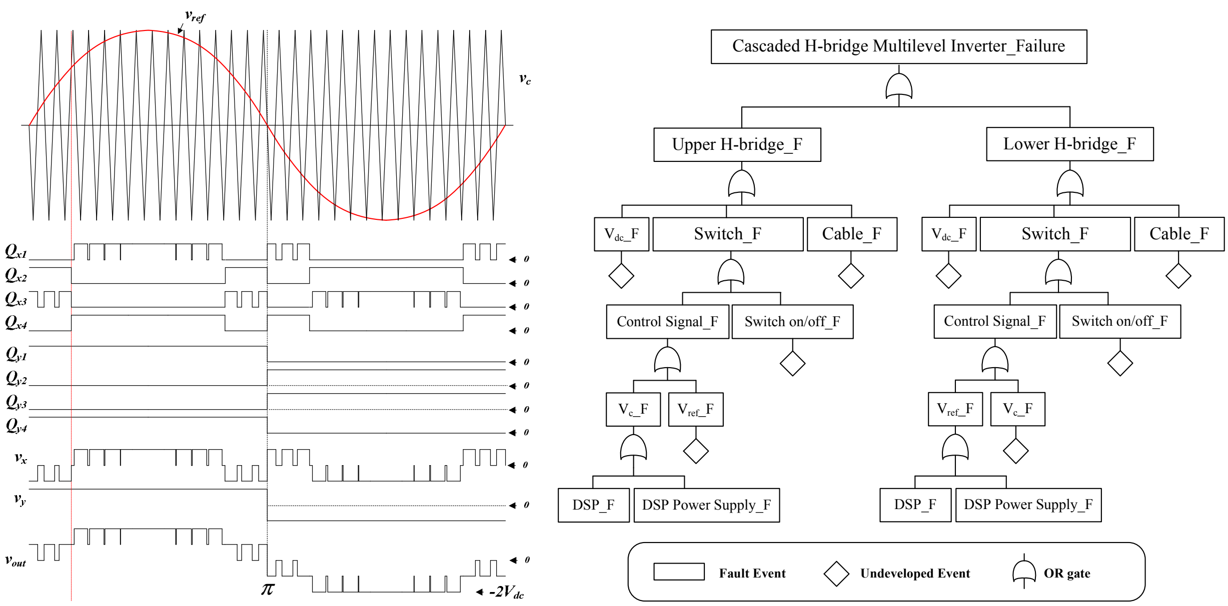

Figure 4: Bipolar Switching, (A) Switching Pattern, (B) Fault-Tree of Bipolar Switching Method

SIMULATION AND EXPERIMENT RESULTS

After Fault-tree analysis (FTA) for general PD, modified PD, and bipolar switching schemes, these three different switching patterns are applied to the same cascaded H-bridge multilevel inverter to verify the validity of the switching patterns and FTA results.

In this simulation and experiment, each input voltage is set to DC 100 [V]. So the peak output voltage becomes 200 [V]. Here, the frequency of the carrier wave is set to 10 [kHz], and phase disposition (PD) method is used to produce control signals.

Figure. 5(a) shows simulation and experiment results of output voltage, reference voltage, upper and lower terminal voltages with a general PD switching pattern. From Figure. 5(a), we can find that four switches are used to generate pulse width modulated waves with high switching frequency. Other switches are working for generating zero-level or fundamental V_{dc} voltage level. On the other hand, from Figure. 5(b), we can notice that two switches in the upper H-bridge cell are working for the generation of PWM waves with high switching frequency. Other switches in the lower H-bridge cell are operated in a fundamental frequency. The energy transferred loads from input sources are proportional to the area of voltage waves. It means most energy is delivered to the load from the voltage source in the lower H-bridge cell. In the modified PD switching method, all switches in the lower H-bridge cell are operated in a fundamental frequency. From this reason, the modified PD switching scheme has a merit for reducing switching losses. However, there is no difference in the reliability and failure rate compared to the general PD method because fault-trees of both switching methods have the same hierarchy. It means that the reliability and failure rate are only depends on the number of carrier and reference waves in the cascaded H-bridge multilevel inverter.

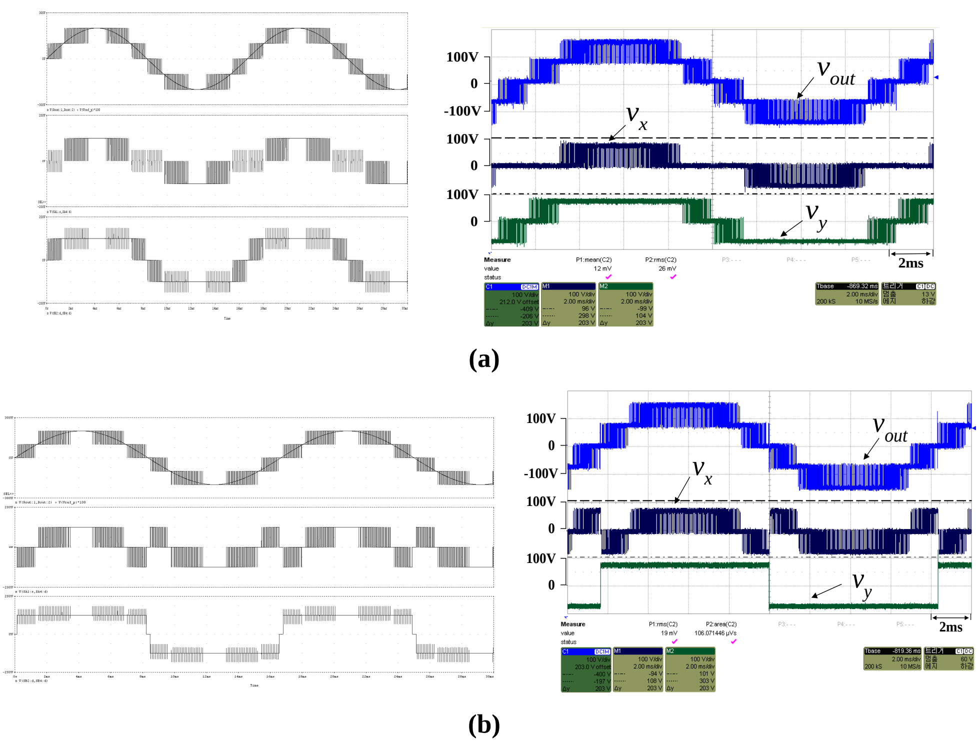

Figure 5: Simulation (Left) and Experiment (Right) Waveforms, (a) General PD Switching Method, (b) Modified PD Switching Method

CONCLUSIONS

Cascaded H-bridge multilevel inverter can apply various pulse width modulated switching scheme such as PD, APOD, bipolar and unipolar voltage switching methods to obtain a sinusoidal output voltage wave and to compensate the lack of H-bridge cells.

For general PD and modified PD switching methods suitable to cascaded H-bridge multilevel inverter, each Fault-tree is given to analyze the reliability and failure rate. After FTA, the switching scheme was verified by simulations and experiments.

As results, the modified PD switching scheme has a merit for reducing switching losses. However, there is no difference in the reliability and failure rate compared to the general PD method because fault-trees of both switching methods have the same hierarchy. It means that the reliability and failure rate are only depends on the number of carrier and reference waves in the cascaded H-bridge multilevel inverter.

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